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14. ABSTRACT
The Global Ocean Data Assimilation Experiment has brought researchers together throughout the globe to address the problem of predicting the ocean environment. A significant step forward has occurred through these efforts, and there exists today operational application of these technologies in areas where historically a strong need has existed alongside the relative lack of mature technical development. GODAE has addressed the necessary technological development for data assimilation, which is a critical choke point within the process of providing meaningful information to many people encompassing a wide range of applications. One of these application areas is for Navies throughout the globe. The importance of the information relayed to ships across the globe is reflected in the dedication of large resources to daily production and dissemination. The importance of the information on which decisions are made daily by the world's Navies throughout the world's oceans is reflected by the commitment of these substantial resources to ensure the GODAE technology enables a new level of capability.

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5.8 Applications from GODAE to Navies throughout the world

Gregg A Jacobs[1], Robert Woodham[2], Didier Jourdan[3], Jez Braithwaite[4]

[1]*Naval Research Laboratory, Stennis Space Center, USA*
[2] *Royal Australian Navy, Australia*
[3] *Centre Militaire d'Océanographie, France*
[4] *Fleet Weather and Oceanography Centre, UK*

Abstract

The Global Ocean Data Assimilation Experiment has brought researchers together throughout the globe to address the problem of predicting the ocean environment. A significant step forward has occurred through these efforts, and there exists today operational application of these technologies in areas where historically a strong need has existed alongside the relative lack of mature technical development. GODAE has addressed the necessary technological development for data assimilation, which is a critical choke point within the process of providing meaningful information to many people encompassing a wide range of applications. One of these application areas is for Navies throughout the globe. Major use by operational Navies of oceanographic information through numerical model forecasts initialized by analysis of global satellite and in situ data sets has allowed substantial advancement in the safety of operations and search and rescue. The importance of the information relayed to ships across the globe is reflected in the dedication of large resources to daily production and dissemination. Not including the costs of observational systems, there are large investments associated with personnel required to ensure that each step of the processing is properly conducted every day. The communications and computational hardware requirements to ensure products are delivered require enormous effort and costs to implement. The importance of the information on which decisions are made daily by the world's Navies throughout the world's oceans is reflected by the commitment of these substantial resources to ensure the GODAE technology enables a new level of capability.

Key words: Navy, ocean applications, modeling, prediction

1. Introduction: Demonstration of GODAE importance to Navies

Nations throughout the globe have invested enormous portions of national wealth into nearshore and deep water Navies to ensure trade, enforce laws and provide relief and aid. The deployed platforms range from small boats carrying a few passengers to aircraft carriers with thousands of people aboard. Away from shore, these investments are at the mercy of the ocean, and day to day changes in the ocean can lead to effects that range from decreased efficiency resulting in lost time and higher costs to failed missions and damage to vessels due to adverse environmental effects to loss in lives. An awareness of the environment in which Navies will be operating leads to decisions changing deployment of assets or use of equipment to mitigate these negative effects. Researchers developing an understanding of ocean physics, representing to ocean physics within computer models and constructing observing systems have made great strides in the past 20 years. The efforts focused through the Global Ocean Data Assimilation Experiment (GODAE) have brought these fields together to clear the hurdle of providing a capability to predict the ocean state and the environmental awareness that is necessary for safe operations of Navies. The importance of the information to operational Navies is demonstrated through the commitment of resources to ensure the necessary personnel, communications, computational capability and infrastructure exists.

Centered on Australia, the BLUElink system uses the Ocean Forecasting Australia Model (OFAM) based on the Modular Ocean Model MOM4 numerical core (Oke et al, 2008; Brassington et al., 2007). Assimilating satellite observations, the system provides twice weekly forecasts out to 6 days for applications such as passage planning and Anti-Submarine Warfare (ASW) exercises. The system must contend with a diverse range of dynamics from tropics to the Antarctic Circumpolar Current. In addition

to the Naval applications, results from the system have been applied to areas from leisure activities such as yacht racing to saving lives during search and rescue at sea.

The Naval Oceanographic Office at Stennis Space Center, Mississippi, provides products throughout the globe based on global and nested model predictions that run on a daily cycle with forecasts from 48 hours such as the global Navy Coastal Ocean Model NCOM (Barron et al., 2007) to 30 days such as the global Navy Ocean Layered Model NLOM (Shriver et al., 2007) depending on the applications along with the global Hybrid Coordinate HYCOM (Hurlburt et al., this issue). These systems draw in the data sets developed through GODAE including satellite data streams and in situ profiling floats. The results are used continually in regularly scheduled Navy exercises in addition to providing aid in emergency response and search and recovery such as the cockpit recorder of the Indonesian airline Adam Air Flight 574 disaster.

The SOAP System (Le Squere and Dombrowsky, 1994) uses outputs from the various systems of Mercator-Ocean consortium (Dombrowsky et al., this issue) to compute products and initialize higher resolution nested model. It has been primarily designed and developed to support anti-submarine warfare at operative level (description of the synoptic scale). It provides products on a daily to weekly basis ranging from classical iso depth maps of sound channel interfaces to high added-value products, such as mesoscale activity analysis, with forecast from 48 hours to 14 days, depending on the applications.

Each of these production centers represents a significant investment in resources for the development of technology, implementation of infrastructure and commitment to maintaining the personnel necessary to ensure regular delivery of operational products. The importance of the GODAE products is demonstrated by the existence of production centers throughout the globe and the commitment on behalf of the Navies that support them. The areas of importance are broad and the impact ranges from small efficiencies to the safety of lives. It would not be possible to provide exhaustive examination of the ocean impact on Navy operations. Some of the major applications that are common throughout Navies of the globe are examined here.

2. Application

Four areas of GODAE model state forecast application are examined here. The first is velocity information, which provides currents for operations under water being conducted at specific points as well as Lagrangian drift forecasts for either in water drifting hazards or search and rescue operations. The second application is ocean thermal and salinity structure forecasts, which are used regularly during training exercises of acoustic systems to first select from the available sensors. Each sensor uses a different frequency range and methodology for detection, and the ocean sound speed structure affects each frequency differently. The performance in the local environment is a key issue in determining what level of performance operations may achieve. At the same time, concern to protect marine mammals leads to areas that may be excluded for use of particular sensors. The intermediary processing of numerical model forecasts state variables to the information used onboard ships to make decisions regarding acoustic sensors is an important consideration on the part of Navies to bring the scientifically validated GODAE capabilities to direct application. Many operations occur nearshore. The prediction of surface waves is vital to determine nearshore surf and the radiation stress that induces alongshore currents and surface currents. Satellite observations of significant wave height now are assimilated into global numerical wave models that drive finer resolution nearshore systems. In one final application, the ocean effects on the atmosphere are included in coupled models in search and rescue as well as drug interdiction efforts to determine the range over which radar systems will reliably detect objects on the ocean surface.

2.1 Forecast Velocity Fields

Velocity fields have important application both from Eulerian and Lagrangian points of view. Operations often occur at specific places, and these naturally lead to requirements for predicted time series at points. A typical example (figure 1) is provided during an exercise off the West Australian Exercise Area (WAXA) during which rescue of a submarine crew was practiced. The first step required grounding a submarine on the ocean floor, an operation that can only be safely conducted in areas in which currents

are sufficiently low. Extreme currents could drag the submarine and cause extensive damage. Next in the exercise, an escape pod had to be attached to the submarine to evacuate crew. This required divers in the water for several hours, also subject to the currents. Predictions over the exercise area were provided by the BLUElink system to ensure the areas and times during which the work was conducted would not be hazardous.

In applications of drifting objects or hazardous material, a Lagrangian prediction can provide trajectory information. The Prestige oil spill during 2002 extended over a very large area, and shifting ocean currents changed the spill path continuously. Crews cleaning up along the shoreline were limited, and inaccurate estimates in spill pathway would result in misplacement of assets, inefficient application of effort, additional environmental damage and subsequent cost for mitigation. SHOM had contributed to the Prestige cleanup effort and examined the problem in retrospect (Figure 2). In this case, drifting particles were injected into a HYCOM reanalysis to determine the accuracy of the prediction system.

The Adam Air Flight 574 disaster in Indonesia during 2004 presented an unfortunate loss of life, and the airline industry works to prevent reoccurrences of any aircraft or human malfunction that leads to such tragedies by the information returned from the onboard flight recorders in aircraft. Unfortunately, the flight was lost from radar, and the position at which it impacted the water surface was unknown. The NAVOCEANO survey vessel Mary Sears was sent to assist with the search, though the area that required searching was so large that finding the flight recorder boxes seemed impossible as the acoustic transmitters within the boxes have limited battery life. Within two days, material from the crash was found washed ashore, and the currents from numerical ocean models at NAVOCEANO were integrated backward in time to estimate the source position (Figure 3). From this information, the Mary Sears was able to locate the flight recorders shortly before the batteries were exhausted.

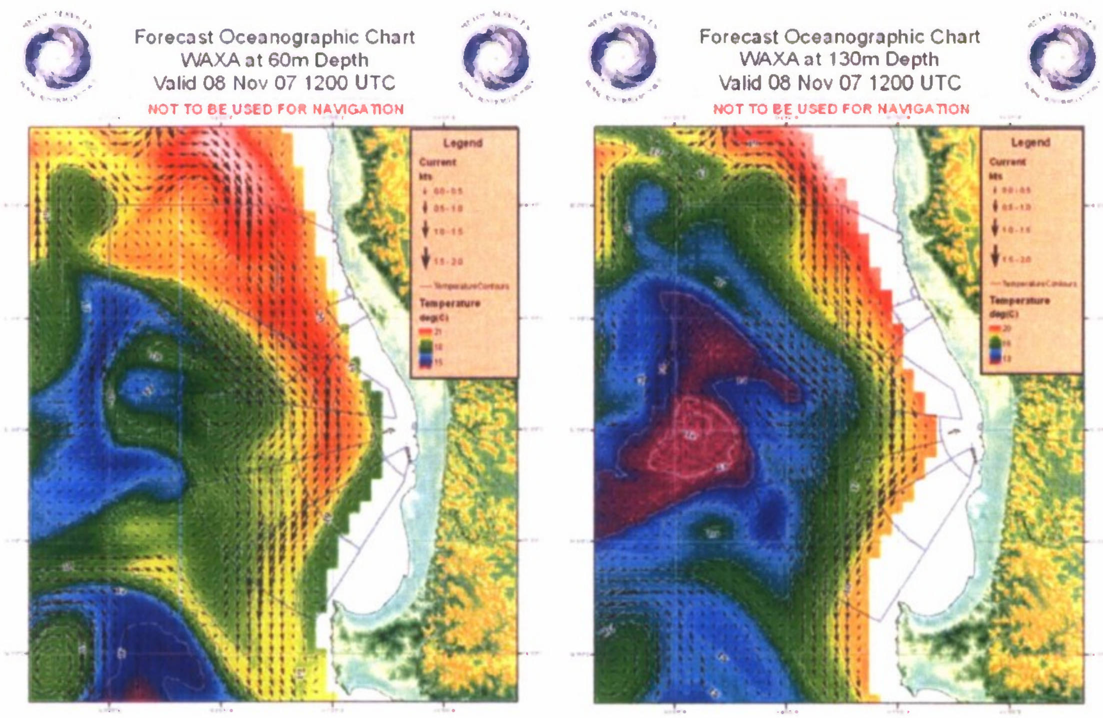

Figure 6: *BLUElink forecast ocean state at 60m depth (left) and 130m depth (right) in the West Australian Exercise Area (WAXA) show velocities (vectors) and temperatures (color) used to determine if training exercises under water may be conducted safely.*

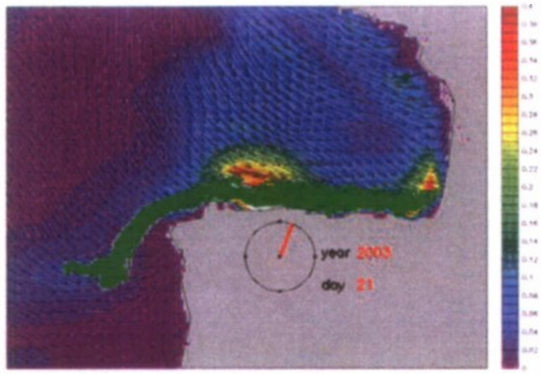

Figure 2: *A reanalysis of the Prestige oil spill that occurred on November 19, 2002 is used to determine the ability of ocean forecast systems to help focus efforts in areas they are needed most. Here, the vectors show surface velocities with color showing the magnitude (m/s). The green area is the position of drifters injected into the model system to show the dispersion of the oil spill.*

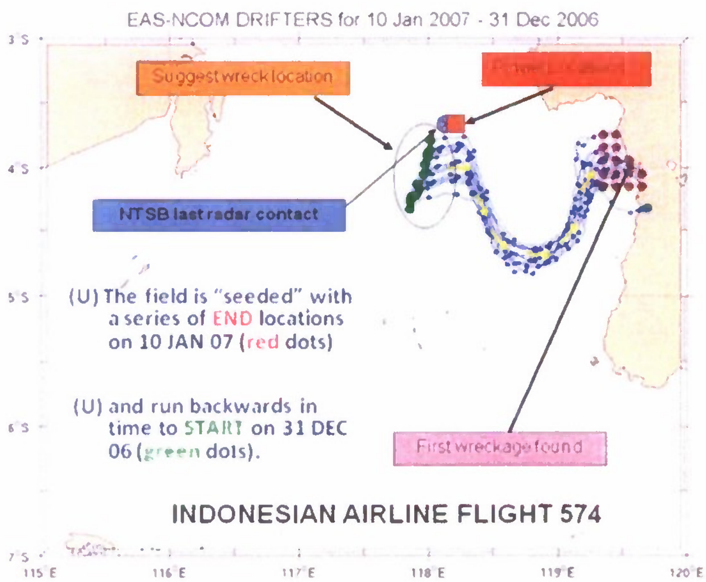

Figure 3: *After the Adams airline flight 574 had crashed, debris had been found off the west coast of Sulawesi. NAVOCEANO used numerical model velocity fields to determine the path the wreckage followed to determine the probable location of the crash site. The black box were located through their acoustic pingers soon after.*

2.2 Forecast Acoustic Propagation

Acoustic energy propagation is extremely important for Navy operations. Acoustic methods are used for communications as well as detection. Continual training is necessary to maintain operator proficiency. Knowing what volume of ocean is ensonified by an acoustic signal controls what sensors may be employed, what frequencies may be used and how the sensors may be used. Ocean properties affect the horizontal and vertical gradients of sound speed, which refract acoustic energy. A hot road in summer generates a warm air layer at the surface and refracts light to create a mirage. Such effects are common place in the ocean due to changes in the mixed layer, upper ocean heat content, small gradients in thermal properties within the thermocline, variations in thermal structure due to ocean mesoscale eddies and even internal waves.

The ability of ocean state nowcast and forecast systems has progressed over time and improves with additional observations. One way to evaluate the performance of ocean systems in an applied manner is to examine how acoustic energy propagates through the ocean state estimate. An observed sound speed structure serves as ground truth, and an acoustic source is placed at 25m. The ratio of energy at any point in the water column at any range to the energy of the source, measured in dB, is the transmission loss. In this case, one observed sound speed profile (Figure 4) produces a large extension of low transmission loss at the depth of the source (25m) due to a surface duct that contains a sound speed increasing with depth causing upward refraction of the energy (Figure 4). Originally, climatology was the best source of information as there was no prediction capability available. Historical observations were averaged to form climatologies, and several disadvantages soon became apparent. First, no synoptic effects were taken into account, and second the averaging process smooths out sharp features in the profile. In particular, the mixed layer depth, which is a key controller of the surface duct. Transmission loss results using climatology result in no surface trapping of energy. When satellite information first became available, only sea surface temperature (SST) was available operationally. There is some correlation of the ocean structure at depth to the SST. Using this correlation to construct the sound speed profile still results in the lack of a surface duct. Altimeter observed sea surface height (SSH) is affected by the thermal expansion due to temperature structure beneath the surface. A temperature profile is computed using temperature at depth correlated to the SSH and SST, and the transmission loss based on this begins to show a surface duct. When an understanding of the physical processes controlling ocean development is used to estimate mixed layer depth, and this mixed layer depth used in the process of constructing the temperature profile, a much stronger surface duct appears. Finally, through the efforts of GODAE, when the satellite observations are used in conjunction with numerical forecast models, a good representation of the surface duct is seen in the transmission loss prediction.

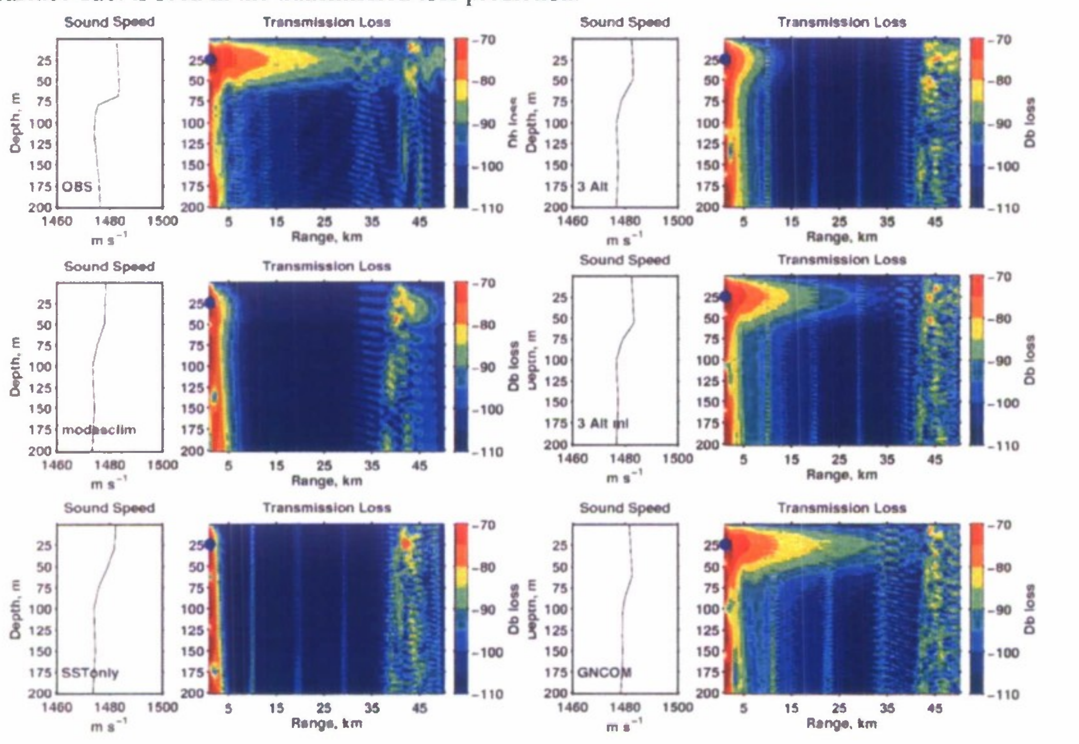

__Figure 4:__ (top left) An observed sound speed profile is used with an acoustic propagation model to construct the transmission loss for a source of sound at 25m depth. The extension of low transmission loss to the right at 25m depth is due to an upward refracting sound speed profile creating a duct. The transmission loss in the other estimates is based on (middle left) climatology, (bottom left) SST only, (top right) SST and SSH from 3 altimeter satellites, (middle right) the same satellite data with the addition of information on mixed layer depth, (bottom right) a global numerical model assimilating the satellite data.

One common purpose of the Navy production centers is to turn the GODAE ocean products into actionable information for people making decisions onboard ships. The temperature or sound speed fields themselves are not of significant use to acoustics operators. An example from the SHOM center shows the steps required to move from the GODAE ocean model state to the actionable information (Figure 5). First, derived information is constructed. This provides indication of the existence of certain acoustically important features. The sonic layer depth (SLD) is the depth of the maximum sound speed in the water column. Above this depth, sound will propagate by long distances by refracting upward. Only frequencies greater than the cutoff frequency will be trapped in the duct, and the cutoff frequency depends on the SLD. The derived information provides indication of how different acoustic signals may propagate. From this, system performance may be determined. Will a particular acoustic system be able to provide the necessary performance for a specific application? Stoplight maps are typically constructed to show where a particular system will perform as expected and where it will not. These are valuable tools, particularly when based on forecast GODAE fields. The positioning of ships, sensors and exercises in advance is greatly aided. Finally, knowledgeable guidance is based on derived information, system performance and human interpretation of the local situation taking into context the end goals of a mission as well positioning and availability of resources. This last step is the most critical and requires well trained and capable staff at the production centers. Without these people, the GODAE products would not have the impact that they presently do within Navies.

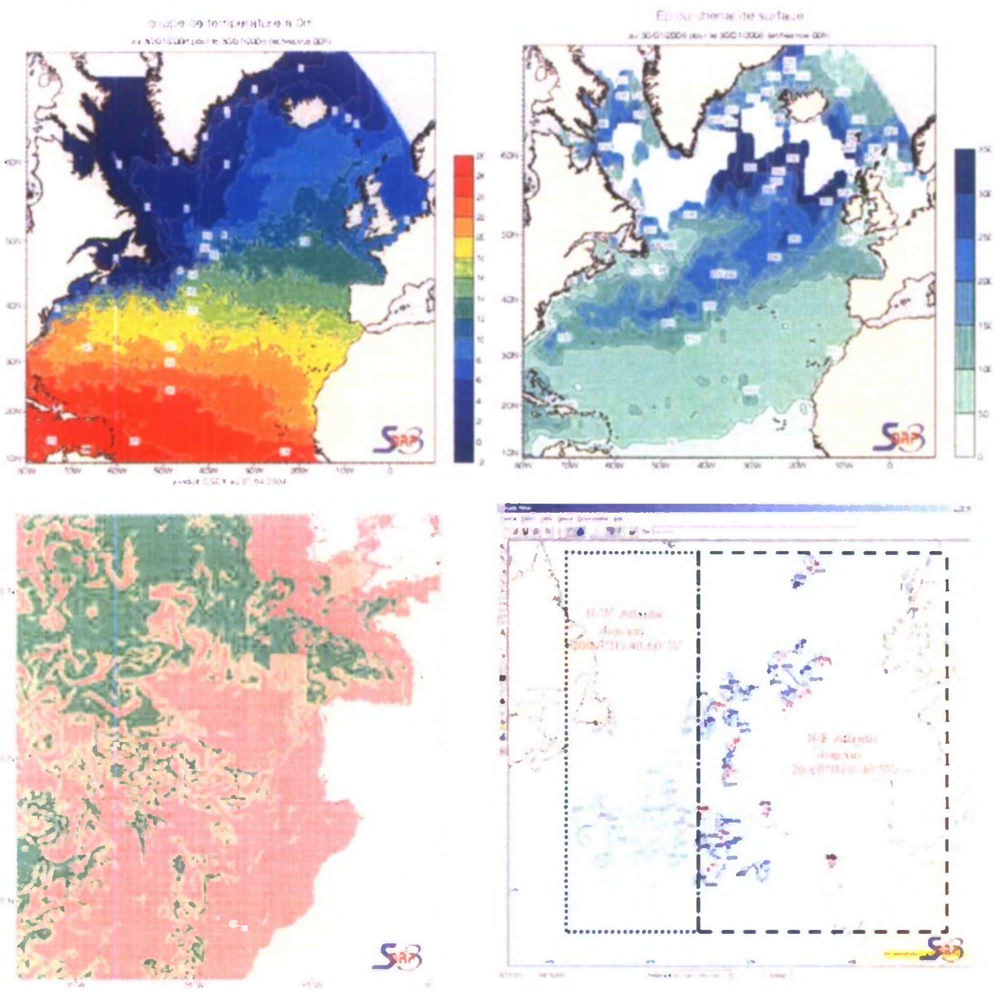

Figure 5: *Operational centers convert the GODAE ocean predictions (top left, SST) into derived information (top right, Sonic Layer Depth), to sensor performance specifications that indicates where a certain sensor will or will not work (bottom left), to actionable information (bottom right) that indicates in what areas ships should or should not operate.*

Finally, training is a necessary part of life in order to ensure people are well qualified to conduct their work. To train safely while avoiding environmental damage is a high concern to all Navies. There are presently requirements on the conditions under which training may occur to ensure that harm to marine mammals does not occur. Unfortunate events in the past have indicated that the energy levels in active sonar systems may cause physical harm and changed behavior in marine mammals. To protect from exposure to possibly harmful conditions, prior to using sonar equipment, personnel are required to determine the extent to which acoustic energy may propagate from the training area. One example (Figure 6) shows the sonic layer depth over an area off southern California. This information is used to determine if there is a surface duct sufficiently deep that acoustic energy will propagate far from the training area.

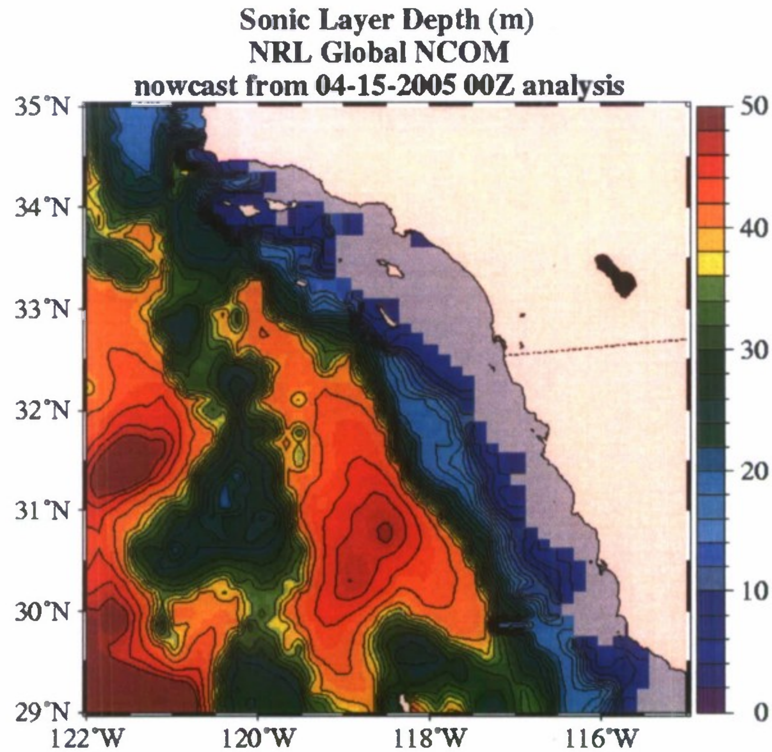

Figure 6: For marine mammal protection, Navies consult information on how acoustic energy will propagate prior to conducting exercises. The sonic layer depth in meters is one indicator of how energy will propagate near the surface. Grey areas have no sonic layer duct.

2.3 Nearshore Prediction Applications

Many operations nearshore are particularly dependent on environmental information, as these operations typically involve divers in the water or small craft. Divers are a mainstay of Navy capabilities, and they are extremely vulnerable to temperature deviations as well as currents that may require large expenditure of energy in order to maintain position. Many operations require moving from the ocean onto shore, and these include both divers and landing craft. The environment and physical processes affecting the environment changes drastically over short distances during the transit. In particular, surface waves become a significant factor. Due to shoaling bathymetry, waves typically steepen and break near the shore. The radiation stress created by the wave field drives currents alongshore and rip currents moving offshore. All these factors have very small spatial scales that are strongly related to the spatial scales of bathymetry. Still, the point at which the nearshore prediction problem begins is at the global ocean deep water scale.

Deep water vessels have operational limitations on the wave conditions under which they may operate, and forecasts of wave heights are critical to safe operations. Ship track routing is one of the largest day-to-day products that Navies use in navigation. Numerical prediction systems represent the wavenumber

spectrum, the energy input due to surface wind stress, dissipation due to wave breaking and other processes and wave-wave nonlinear interaction. Swell energy can propagate around the globe, and thus a global wave model is necessary. The typical problems that occur are due to inaccuracy in surface wind forcing and inaccuracy in numerical model predictions. These deficiencies can be corrected to some degree by assimilation of observations in which altimeter-observed significant wave height is used to adjust the energy spectrum within the numerical model (Figure 7).

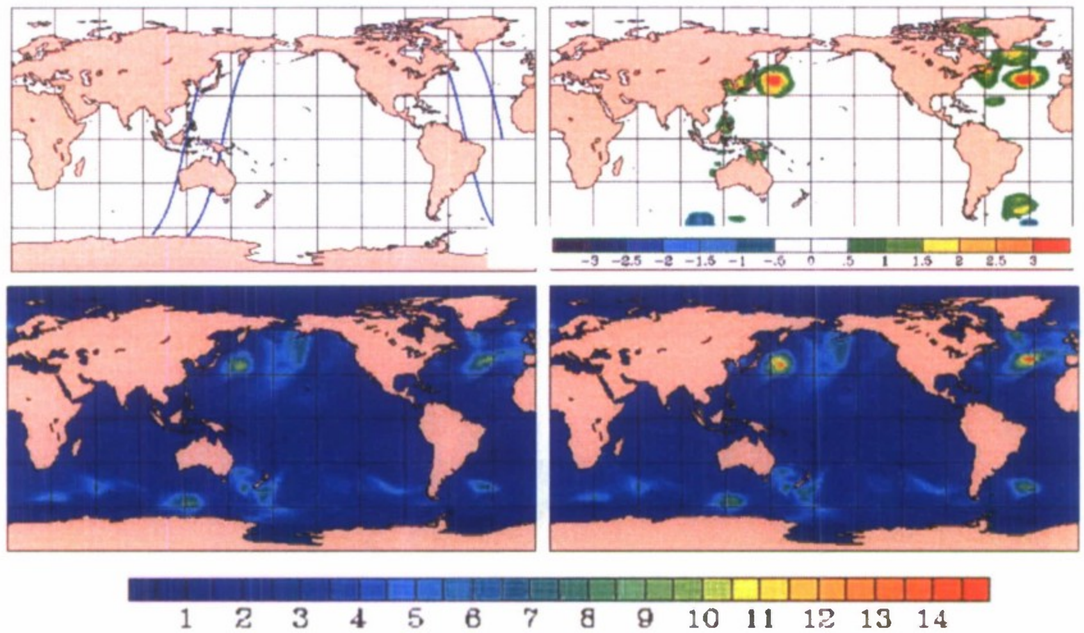

***Figure** 7: Altimeter-observed significant wave heights along satellite ground tracks (top left) is differenced from a numerical model forecast to construct the analysis increment (top right in meters). The model forecast wave height (bottom left in meters) is corrected to provide the new initial state (bottom right).*

The global models provide boundary conditions to higher resolution models that contain much greater representation of physical processes. Blocking by islands or small land features is not taken into account in the global systems, and the breaking wave effects are significant only in very shallow water where the global models do not contain sufficient resolution. These models also couple to circulation models to take into account the Stoke's drift forcing from the wave field to hydrodynamic flow. One example during an exercise at Pohang Harber, Korea is shown in Figure 8. The domain is 2km by 2km. The effects of wave blockage are apparent in the harbor on the lower left, and the field generates a flow toward the southwest along the western boundary and to the east along the harbor. The wave height and currents are combined to provide operators information on the safety of conducting landing operations at any point along the coasts.

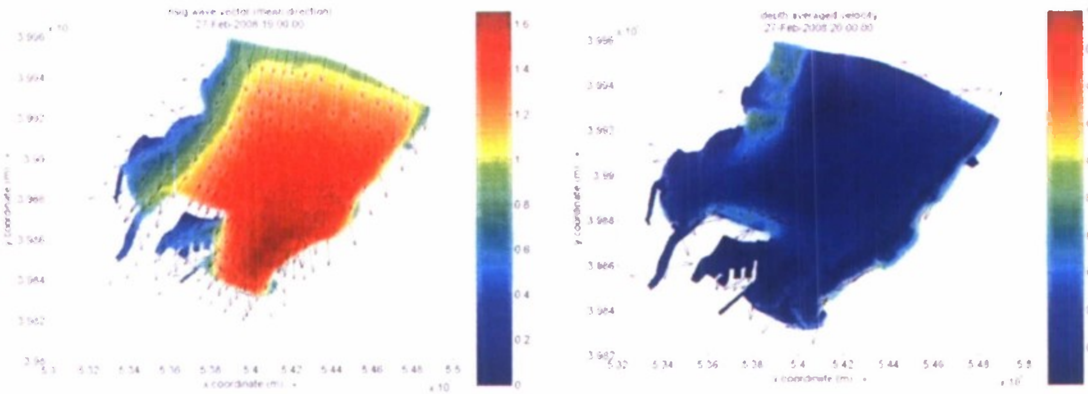

__Figure 8:__ An example of high resolution forecasts for wave height (left in meters) and currents (right) with vectors showing direction and color showing magnitude in m/s. Such high resolution systems are driven by boundary conditions from global wave forecasts assimilating observations.

In addition to the wave field, temperature is an important controlling factor for determining the ability to perform diver operations and the time period a diver may survive in the environmental conditions. An example of constructing actionable decision information from GODAE products is shown in Figure 9. Both the currents and temperatures are used in a decision analysis aid to produce a map that shows areas in which diver operations may be conducted, where conditions are marginal and where diver operations should not be conducted. In the example here, it is mainly the areas of high velocities that would prevent divers from maintaining position.

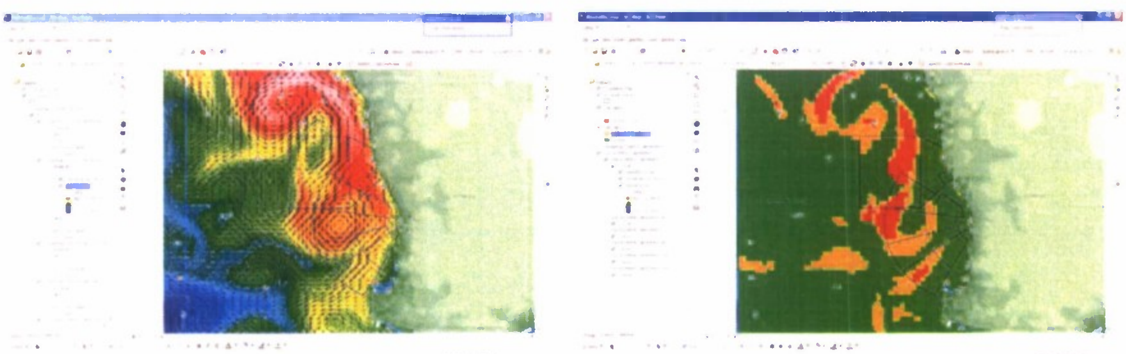

__Figure 8:__ Surface currents and temperature (left with vectors showing currents and color indicating temperature) provide the limiting environmental information for diver operations (right) in which red indicates areas in which currents are too high, orange are marginal areas and green represents areas in which it is safe to operate.

2.4 Coupled Atmospheric Effects

The ocean and atmosphere exchange heat and material at the interface, and the ocean environment evolution strongly affects the atmosphere due to the much greater heat capacity of the ocean. The evaporation of moisture from the ocean creates a duct in the atmosphere that controls radar propagation. Knowledge of the distance a radar signal will propagate is important when searching for objects on the ocean surface. These operations usually involve search and rescue as well as drug interdiction. In order to predict the atmospheric properties, it is necessary to include the interactions with the ocean. The BLUElink system contains a high resolution nested coupled ocean and atmosphere prediction system that exchanges information between the two to provide forecast environment. From the forecasts, derived information on sensor performance is then obtained (Figure 9).

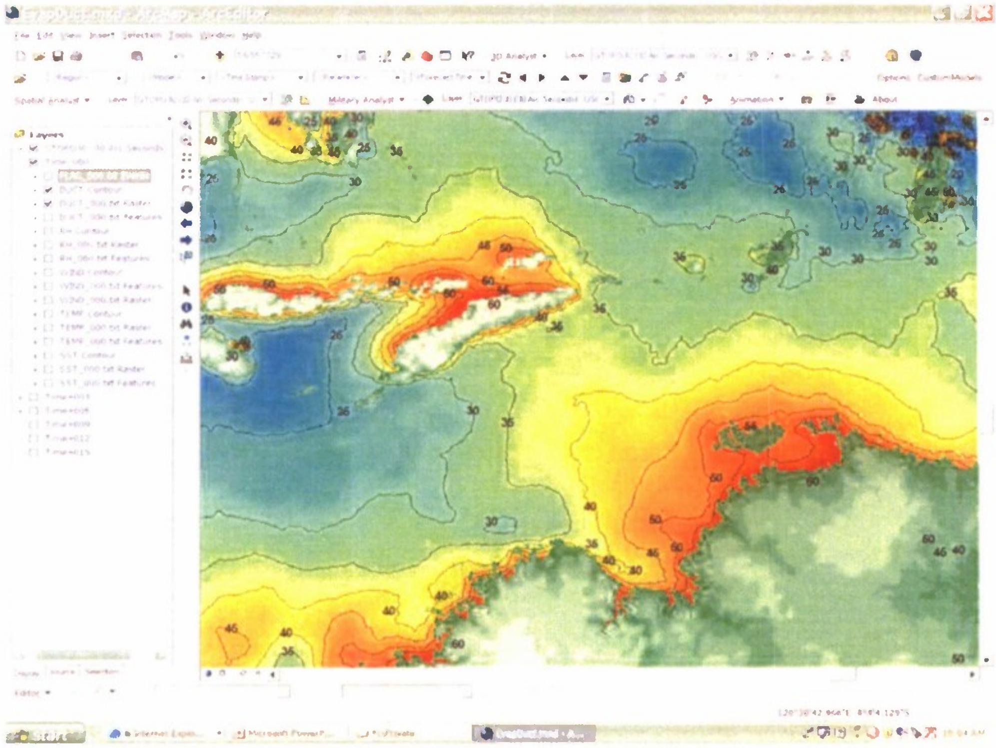

__Figure 9:__ Evaporative duct height in meters forecasted by a the BLUElink coupled ocean / atmosphere model system.

3. Conclusions for the Future

The GODAE results have enabled a first generation of ocean prediction capability that has proved value to the Navies of the globe. The dedicated investment in infrastructure, transition of technology capability and commitment of personnel to guarantee that the products will be produced daily for the people who need them demonstrates the importance of these products. The applications examined here are just a few of those that are used daily. The science community strives to understand underlying physics of problems and prove the knowledge through demonstration. This work has culminated in the systems in place today. With this first taste of the possibilities, great interest has risen within Navies. In particular, the accuracy of the systems in terms of the impact on operations is of high interest. Operators are only beginning to become experienced in the system accuracies and applications. Development of end application performance is under way in many areas. Some simple examples from meteorology are tropical cyclone track prediction and the impact that inaccurate forecasts may have on wasted resources to evacuate unnecessarily or lost lives due to incorrect evacuation areas forecasted. The operational Navies do not yet have the answers as to how accurately the mesoscale field must be predicted or how accurately the vertical temperature structure must be. The GODAE demonstration has certainly piqued interest, and with the realization, that ocean prediction is feasible, efforts to quantify these requirements are under way.

New possibilities have come to light in the operational centers, which had previously worked under the assumption that the only information available would be in situ observations. These observations were typically out of date by the time they reached the operational centers (anywhere from 12 to 48 hours), and by the time the center provided information to end users the value would degrade further. Having realistic ocean forecasts has made every ocean observation crucial as it provides increased fidelity in forecasts. With these forecasts, sensor system performance prediction and new actionable information is being provided. Entire new lines of products have opened up with the successful conclusion of GODAE, and the continued construction of new products has no end in sight.

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